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Requirements for Designing A Robotic System for Aircraft Wing Fuel Tank Inspection

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ABSTRACT

This paper presents the requirements for a robotic system to carry out inspection of fighter aircraft wing fuel tank, typical of challenging harsh environment. The research investigates the challenging case of fighter aircraft wing tank inspection. The wing shape geometry is highly irregular with very few fixed cartesian reference points. The internal structure is congested with many systems and difficult to manoeuvre within. This paper summarizes the key requirements for inspection robotics for fighter aircraft wing tank inspection.

The requirements are presented in three categories; i) Robotic locomotion and navigation imposed by the complex and confined space inside the wing structure, ii) the materials, mechanisms and power sources imposed by the hazardous and potentially explosive environment inside the wing tank and lastly, iii) the inspection sensors and assessment algorithms to detect fuel tank defect and degradation features. The authors focus on the flexibility and mobility challenges to overcome the numerous obstacles within the confined space whilst effectively integrating a visual inspection technique to capture defined defects. The paper starts with an overview of existing maintenance practices, highlighting the implications and challenges of these methods. Their limitations inspire the development of novel robotics to achieve detailed internal inspection of an aircraft wing fuel tank. A design concept is proposed together with the validation test methods.

1. INTRODUCTION

An aircraft wing is a complex structure which is constructed of various physical mechanical components such as the wing skin, rib and spar structures, fuel transfer holes, fuel and hydraulic lines and electrical wiring. An aircraft wing has several key purposes, one of the most significant being as a storage area for the jet fuel, also known as an integral wet wing fuel tank since the fuel is stored directly into wing structure. The geometric dimensions of an aircraft fuel tank differ according to the type of aircraft. Commercial aircraft fuel tanks are larger than that of streamlined fighter jet aircraft.

Thorough strategic maintenance procedures involving inspection and modifications are conducted to ensure the integrity of the wing and the full functionality of the fuel tank. The fuel tank has a combination of the following three characteristics which makes it a challenging area for inspection:

1. Confined space of the fuel tank meaning that there is restricted access.
2. Jet fuel has toxic characteristics leading to a risk of fire and explosion.
3. Oxygen deficiency within the fuel tank.

Due to the combination of both physical and atmospheric hazards vigorous preparation is required before close contact or entry by personnel.

For this particular project the key focus to develop the concept of an inspection robotic system for fighter aircraft wing fuel tank, representative to the Eurofighter Typhoon. The Typhoon is a supersonic aircraft with extremely thin canard delta shape wing design. The fuel tank within the wing is separated into two sections known as the FWD and AFT integral fuel tank. The fuel tank dimensions are narrower towards the outboard section of the wing, where the area of inspection is difficult to reach due to the confined space. Figure 1 is a visual representation of the Typhoon wing structure with multiple spars attached to the lower panel, showing the details of the fuel transfer holes (Geographic, 2012).

For this research a strategic engineering design methodology is followed:

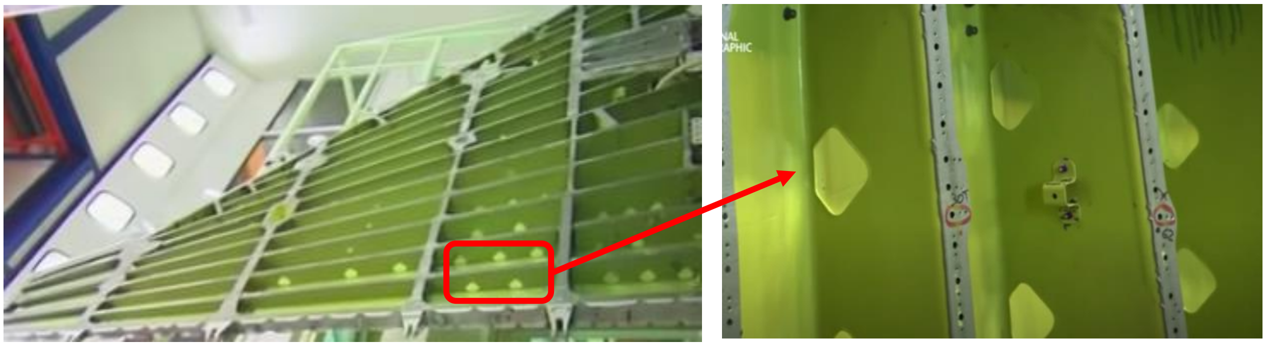


Figure 1. Typhoon multi spar wing panel structure and fuel transfer holes (Geographic, 2012).

1. Define the purpose of use of the robotic system, this involves defining the requirements and constraints and the problem to solve.
2. Kinematic analysis involves defining the geometry of the robotic system such as system dimensions.
3. Brainstorm ideas with the use of sketches and Computer Aided Design (CAD) software for virtual simulations and testing.
4. Manufacturing of physical components with 3D printing.
5. Validation of robotic system through several experimental tests.

This paper reports on the initial stage of development of a robotic system, which is to define its requirements. The requirements elicitation phase involves understanding the application domain, the specific problem to be solved, how the system should behave, the organizational needs and constraints and the specific facilities required by the system stakeholders (A.Danyllo, 2017).

The paper demonstrates the development of a suitable set of requirements that the robotic system should successfully achieve which is discussed in further detail throughout the paper. The following section highlights the procedures of current manual practice of fuel tank inspection.

2. AIRCRAFT FUEL TANK INSPECTION

The key purpose of inspection is to identify any discrepancies that may hinder the functionality of a system. Different types of defects can be found within a fuel tank such as surface damages, fuel leaks and microbiologically initiated corrosion. Visual inspection or Non-Destructive Tests (NDT) and the main means to detect these and initiate any appropriate repairs.

Current maintenance practice of inspecting the fuel tank involves a qualified engineer entering the fuel tank through a small opening in the wing, in which they are required to manoeuvre within the fuel cell compartments, equipped with necessary respiratory equipment and Personal Protective Equipment (PPE) for protection. This process works better in larger wing structures. Inspection of smaller aircrafts are conducted with the use of Remote Visual Inspection (RVI) equipment such as a borescope which is fed through an access hole from the top of the wing.

The engineer using a borescope to inspect narrow spaces may also need to remove certain panels to gain access since physical entry is not possible. Borescopes are popular for visual inspection of difficult to access areas due to their flexibility and miniature size, with diameters varying between 5mm – 8mm. The current maintenance practice could expose the engineers to harmful environment for an extended period of time. Squeezing into confined spaces is

In this context, confined space is defined also a challenging task. as an area large enough for an individual to enter and perform work but has limited and restricted means of entry and exit and is not designed for continuous occupancy (C.Joseph, 2002). The Piper PA-28 aircraft have faced problems relating to the difficulties of inspection in confined space, where wing spar corrosion is becoming a serious issue in hard-to-reach spaces and inspection is challenging. Without appropriate maintenance to tackle this, it can lead to fatal failure (Federal Aviation Administration (FAA), 2020). The FAA has introduced regular inspections and new access panel installation on the wing to access these confined areas or preferably conduct wing removal.

Lufthansa Technik have also raised their concerns with fuel tank inspection implications where towards the outer tip of the wing the structure becomes narrower and lower and the frames with narrow openings make it difficult to access the spot where the defect is located (DRÄGER, 2020). Therefore it is important to tackle this common problem hence introducing a robotic system that can create a solution for confined space inspection would be suitable.

2.1. Fuel tank inspection preparation

The following section gives an overview of fuel tank inspection from the US Military technical manual (USAF, 2019), this procedure applies similarly to all maintenance of aircraft fuel tanks. Extensive preparation is required in order to bring the fuel tank to a safe condition for inspection. The initial procedure involves emptying of the fuel tank and

(a) Fuel tank ventilation. (b) Inspection in confined space.

Figure 2. Aircraft fuel tank preparation and inspection (Aircraft fuel tank purge and entry equipment, n.d.).

ventilation before close contact or physical entry into the wing as shown in Figure 2 a) and b).

Before the aircraft fuel tank is opened, standard procedure involves a comprehensive checklist to ensure all purging and ventilating equipment is operational (Aircraft fuel tank purge and entry equipment, n.d.). Fire safety is extremely important, easy access to fire extinguishers and emergency communication should be readily available. The atmospheric monitoring system is fully functional as it continuously monitors the vapor inside the tank and oxygen levels which should be at 19.5% and not drop below this limit.

The initial opening of the fuel tank is a dangerous task due to the high concentration of Volatile Organic Compound (VOC). Hence it is important to adhere to the strict safety precautions during the purging process.

Purging is done to reduce the dangerous levels of VOC PPM (Parts Per Million) within a fuel tank and reach a certain LEL (Lower Explosive Limit) level in order to ensure that it is safe enough for an engineer to enter the tank for repair. Ventilation is a continuous process required throughout inspection to maintain a fresh supply of air.

The wing box is constructed from rib and multi spar structures. Additionally, there are other systems present, ranging from sensors to measure density, fill level and temperature of the fuel, power units, pumps and cables from which data is gathered and transferred to the cockpit.

If one of these systems develop a fault, then it is required for the engineer to go as close as possible to the area of inspection. Essential tools such as lighting source, drill and borescope are designed to be explosion proof. If the equipment does not fit the required specification, there could be the possibility of spark and ignition in which the combination of fuel vapor and oxygen reaches a temperature of 38℃ and can lead to serious consequences.

Electronic equipment used within the fuel tank premises such as flashlights for inspection within the dark conditions, mobile radios to maintain communication between engineers should be listed for National Fire Protection Association (NFPA) 70, Class I, Division 1, hazardous areas, (e.g., tested to MIL-STD-810 or equivalent standard) otherwise approved by competent authority for National Electric Code Class I, Division 1 or 2 hazardous areas (USAF, 2019).

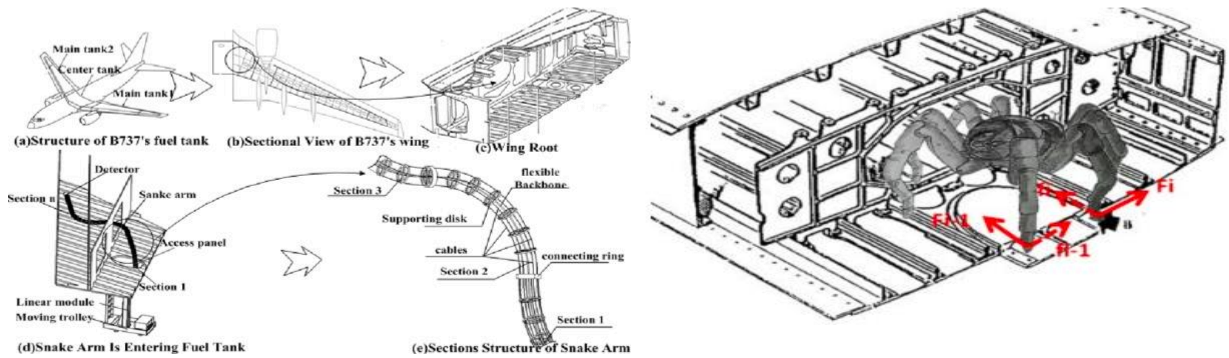
Primarily non-intrinsically powered electronic equipment should remain outside of the fuel tank. However, if it is necessary for the use of a non-approved equipment within the fuel cell the fuel tank should be purged to 300PPM (5 percent LEL) or less and the tank should be continuously monitored and ventilated. Non approved equipment may include a computer, e-tools and digital cameras. Appropriate levels of LEL should be met to allow non-intrinsically equipment near or around aircraft. The following section discusses the existing research on development of robotic systems for aircraft fuel tank inspection, emphasizing the limitations of these particular designs and the overall implications of introducing robotics to such an environment.

3. CURRENT ROBOTICS FOR AIRCRAFT FUEL TANK INSPECTION

There is currently a limited number of publicly known robotic system for aircraft fuel tank inspection. Two are explained here. The first is a continuum snake arm robot. The purpose behind this design choice is the benefits of flexibility, which is achieved by attaching multiple discs by cords, as illustrated in Figure 3 a) (N.Guochen, 2013).

These are controlled by several electronic motors found at the base of the arm which remain outside of the fuel tank to ensure that there is no cause of spark or ignition within the fuel tank. The flexibility within this particular robot design allows movement around obstacles but requires complex control. However, there is the limitation of how far the robotic arm is able to reach within the confined spaces of the fuel tank. This robotic design has been developed for larger commercial aircraft similar to the B737 therefore the physical dimensions are much larger than what is suitable for a Typhoon fighter.

The second reported robot is a proposed mobile hexapod design that is able to walk through the fuel tank with the use



(a) Continuum arm robot design (N.Guochen, 2013). (b) Hexapod robot design (Gaina.Maria-Giorgiana, 2019).

Figure 3. Continuum arm robot design and hexapod robot design.

of its multiple limbs, however the chosen locomotion method and size of the robot system is not suitable for the congested environment, especially when reaching confined spaces of the aircraft as shown in Figure 3 b). It also requires precise control of each of the 8 limbs. There is also the danger of a limb becoming wedged between the obstacles within the tank (Gaina.Maria-Giorgiana, 2019). Apart from the two examples of proposed robotic systems, there has not been further study focusing on actual development and application of robotics for aircraft fuel tank.

This leaves a gap in knowledge of understanding the key characteristics of a fuel tank environment and applying the implementation of a successful robotic system to conduct inspection in difficult spaces. Other industries such as oil and gas, nuclear decommissioning have been developing robotic systems over several years and are much more advanced in the level of developing and implementing miniature robotic designs that are able to manoeuvre within complicated pipelines and be able to withstand hazardous material such as oil residue.

They have overcome some of the challenges related to robotic inspection in confined spaces. There are many examples of pipeline inspection robots incorporating different methods of mobility primarily flexible robotic snakes that contain a number of modular sections. Some of the inspiration behind the project is based on research predominantly found within these industries.

4. FIGHTER AIRCRAFT WING TANK

The following physical parameters are key components of the Typhoon fuel tank:

1. The multi spar structure consists of 16 spars panels including front and rear spar. The distance between each spar is approximately 70mm-80mm at the root of the wing and narrows down to 30mm-40mm towards the wing tip. The change in distance between the spars is due to the delta wing shape.
2. Fuel transfer holes are found throughout the spar structures and are approximately 70mm in diameter.
3. The transfer holes are found 11mm above the floor of the wing skin.
4. The distance between each hole is roughly 130mm-140mm apart in a linear formation.
5. The rib structure formation across wing consists of 4 rib panels 7m-8m length at root of wing and 1m-1.5m at outboard.
6. Two cable conduits running in line with the spar structure starting from the root of wing towards wing tip approximately 2m-3.5m in length, with a diameter of 30mm-50mm. There are also inboard and outboard elevon hydraulic actuators.
7. Presence of jet fuel residue throughout wing fuel tank.

Table 1 illustrates the requirements and parameters that are important for the development of the robotic system which are discussed in further detail in the following section.

5. DEVELOPMENT OF SET OF REQUIREMENTS

Requirements are a fundamental part of all projects. If the requirements are inconsistent and do not achieve the proposed outcome of the project, it can lead to the development of a system that does not meet the desired purpose. For this project a set of requirements have been constructed based on the need of a robotic system for inspecting a fuel tank environment. ISO standards have been used as a basis for specifying requirements and guidelines for the development of the robot system. Each requirement is evaluated in detail to ensure that it meets the necessary outcome.

A brief description of performance criteria focusing on the mobility aspect of the robotic system is illustrated. All test paths are parameterized with respect to the size of mobile platform. Length unit LU is defined as the maximum of the width *w* and the length *l* of the mobile platform.

Table 1. Explicit requirements and parameters.

	Explicit Requirement	Parameters
1.	Robot should fit within the dimensions of the fuel tank.	Fuel transfer hole dimension 70mm. Largest distance between spar panels 70mm-80mm. The height and width of robotic chassis should be approximately between 40mm - 50mm.
2.	Robot should move within the confined spaces of the fuel tank.	Flexibility in locomotion method is important. For example, movement from one fuel transfer hole to opposite fuel transfer hole a steering angle of approximately 30°- 45° for chassis should be feasible. Adjacent fuel transfer holes found in same spar a rotation of 90°-180° should be achievable by chassis.
3.	Robot should conduct visual inspection.	Noticeable visual defects of corrosion such as rust or slimy growth. Adequate lighting and camera field view of 80°(30mm) -107°(28mm).
4.	Robot should navigate around obstacles.	2 cable conduits approximately 2m - 3.5m in length, with a diameter of 30mm - 50mm. The transfer holes are found 11mm above the floor of the wing skin.
5.	Robot should withstand the hazardous environment	Entry safe conditions of non-intrinsic safe equipment is 300 PPM. Oxygen concentration between 19.5-23.5 percent. Levels above 23.5 increases the risk of a fire.
6.	A retrieval method in case of failure.	Tether should be approximately 3m - 4m in length and tether diameter between 5mm - 8mm.

1. The turning width: The purpose of this test is to determine the turning width for the specific type of turning of the mobile platform (International Standards Organization (ISO), Robotics - Performance criteria and related test methods for service robots Part 1: Locomotion for wheeled robots 18646-1:2016, 2016). In this case, taken into consideration is the distance between the spar panels for the robot to turn in is determined by mechanical characteristics such as steer angle. Three common types of turns used are: U-turn, 3-point turn and L-turn. This would be tested by placing robot in a test facility with several physical wall heights higher than the robot along with collision avoidance.
2. Mobility over a sill: The purpose of this test is to determine the maximum sill heights the robot can pass over. For short sills the robot should have a sufficient ground clearance so that the body of the robot does not touch while passing over (ISO, 2016). This applies when the robotic system moves over the 11mm elevation of fuel transfer hole.
3. Obstacle detection: The purpose of this test is to determine if the robot is able to detect obstacle and measure the distance to obstacles of different geometry. Obstacle avoidance to determine the ability of a robot to prevent a collision with static or dynamic obstacle, either by stopping or conducting appropriate evasion movement (International Standards Organization (ISO), Robotics - Performance criteria and related test methods for service robots 18646-2:2019, 2019).

Evasion movement would be principal for the robotic system in a complex space therefore, a minimum distance of 0.02mm - 0.03mm between obstacle and robot should be defined.

5.1. Fit within the dimensions of the fuel tank

The following factors shall be taken into account during the layout design process: workspaces, access and clearance. Identifying the maximum space of the robot system, establishing restricted and operating spaces, and identifying the need for clearances around obstacles (International Standards Organization (ISO), Robots and robotic devices — Safety requirements for industrial robots Part 2: Robot systems and integrations.10218-2:2011, 2011). There are multiple constraints within the fuel tank structure with the dimensions of the fuel transfer hole being the primary parameter. The shape of the transfer hole is in the shape of a pentagon with rounded edges. The width between the two largest points is 70mm and the height from top to the bottom is 49mm. Several of these are found across the length of each spar as illustrated in Figure 1.

This therefore indicates that the size of the robotic system has to be relatively compact to fit within these specified dimensions. To successfully accomplish this requirement a miniature robotic system should be designed with the use of small-scale mechanical components. The physical dimensions of the robotic system should be approximately within the limits of 40mm – 45mm in height and width whereas in the length of the chassis can vary between the limits of 80mm – 100mm although it has to be not long enough to become wedged within surrounding structures.

The overall chassis of the robot shape has to be narrow in width similar to a continuum arm robot. This includes taking into consideration the dimensions of the chassis assembly, the mechanical parts such as motor size and sensors on board the mobile platform.

5.2. Effective mobility method for confined space

The choice of a locomotion method for the mobile robot is extremely important, especially within a complex environment as there are many constraints present the robot is obligatory to manoeuvre around. The physical parameters of the fuel tank highlighted in Section 4 have to be considered throughout the design phase of the robotic system. The choice of driving mechanism for the robotic system chassis is the first key parameter to determine. A track mechanism seems to be the most suitable choice for this particular use case as it has many advantages. For example, overcoming the numerous elevations on the floor of the fuel tank of 11mm, and moving through fuel residue puddles. The selection of a track design has the ability to spread the contact load over a larger surface area.

Rubber tracks would be the most applicable due to better traction and less slippage over most surfaces and rubber has high intrinsic friction and melds over uneven surfaces. Whereas if a standard wheel driven robot design was considered there may be several restrictions such as not being able to navigate over uneven terrain and obstacles well enough and the occurrence of wheel skid in the presence of jet fuel. The same problem would apply to a walking robot with limbs which would be difficult to move and control between the various elevations and fuel system piping. The width of the tracks should be approximately 40mm in width so that there is enough clearance between the circumference of the hole and the robot.

5.2.1. Robot system payload

The tracks should be robust and manage the payload of the robot weighing between 2Kg-4Kg. The payload of the robotic system as to be suitable enough so that the robot does not tumble over and is able to withstand the weight of the additional sensors on board and the telescopic mechanism. The robotic system should be flexible yet rigid, to carry onboard inspection equipment. The payload of the robotic system should be between the limits of 1.5Kg-3Kg.

5.2.2. Robot system flexibility

The next step is to take into consideration the physical component dimensions within the fuel tank that the robotic system would manoeuvre around and incorporating flexibility into the robot. The fuel transfer holes are not parallel with each other throughout the multi spar structure therefore incorporating modulation within the robotic system creates a flexible rotational joint which is essential. If the robot is required to move from one fuel transfer hole across to another it will have to turn approximately 30-45° angle from one spar hole to the next spar hole. The angular rotation of flexibility in the modulation system should be between the limits of 90°-180°, this is necessary if steering the robotic system through one fuel transfer hole into another along the same spar similar to make a U-Turn path.

5.3. Conduct visual inspection in confined space

Operators conduct visual inspection to recognize any areas of corrosion or defects that are noticeable to the eye. Inspectors scan the floor, sidewall, or other areas being monitored with their eyes, trying to determine whether: existing corrosion has grown or if there are new areas with corrosion such as discontinuity in the surface. It is important to identify the types of defects found in the fuel tank as this provides the basis of the selection of technology needed to assess these faults. The most common types of defects found are Microbiologically Initiated Corrosion (MIC) which occurs with the presence of jet fuel and water and has the appearance of sluggish brown, green colour (CAA, 2017).

Microbes have a preference to thrive on surfaces in a film of slimy growth, known as a biofilm. MIC of aluminium alloys in aircraft wing tanks and is typified by etching and/or pitting corrosion which may progress at rapid rates. Aging of fuel tank system components and various kinds of debris can be found inside fuel tanks including chaffing of electrical power wires routed in conduits, corrosion of bonds and connections between parts. NDT methods such as Ultrasonic Testing (UT) testing are most commonly used for detecting deep areas of corrosion.

The key purpose of the robotic system is to visually identify defects, therefore the camera onboard the robot should capture images that are transmitted back to the operator to visually identify signs of corrosion, which appears as a discontinuity in a material, such as a discoloration or some other change to its appearance. Tracking the growth of corrosion can be done by using a measuring tool, by taking photographs.

5.3.1. Lighting for dark conditions

The robot system shall be supplied with integral lighting suitable for the operations concerned despite ambient lighting of normal intensity. The robot system shall be designed and constructed so that there is no area of shadow to cause nuisance, no irritating dazzle and no dangerous stroboscopic effects on moving parts due to the lighting. Internal parts requiring frequent inspection and adjustment, as well as maintenance areas, shall be provided with appropriate lighting. Illumination shall be at least 500 lx at the area where frequent inspection and adjustment is necessary. Example of borescope specification camera that can be used on the robotic system : LED illumination – Number of LED – 2 (white) with a camera field view of 80°(30mm)-107°(28mm).

5.3.2. Visual inspection in confined space

The development of the robotic system focuses on confined space inspection and how effectively it can reach these spaces. In order to fulfil this requirement an extendable and retractable actuation mechanism (arm manipulator) can be integrated onto the platform of the robot. The key design requirement of the manipulator arm is that it should have slow controlled movement so that it doesn't create strong impact in the case of a collision. This also means that the payload of the compact manipulator should be light at approximately 34g. The length of the actuation system when completed retracted should be between 40mm-50mm with a stroke of 30mm and positional accuracy of 0.2mm ideal for tight space requirements.

5.4. Navigate around physical obstacles

Obstacle avoidance can be initiated with the application of proximity sensors which are important to be part of the robotic system to prevent collision and turn into a different direction, this is also why flexibility is extremely important of the robotic system to ensure it is able to bend and turn within a small space. Proximity sensors for position detection of moving mechanical parts can be applied to detect how far for example the actuation arm has expanded in length so that it does not clash into other components.

The most suitable method to control the robotic system within such a complex environment is by teleoperation where there is bidirectional communication, control and command between the operator and robot. The operator is able to manually control the movement of each of the robot mechanical parts with the use of various sensors and cameras on board. The operator may use a visual display user interface unit. The operator also has the benefit to control the robotic system from a safe distance which is very important when controlling a robot within a hazardous environment.

Teleoperation also ensures safety since the operator is able to control the robot taking into considerations the surrounding physical components. The diameters of the conduits are approximately 20mm-30mm therefore, these dimensions have to be taken into consideration to ensure that the robotic system chassis is able to move around these dimensions.

It is important to that the robotic system may not be able to completely avoid contact with physical components within the confined space. The selection of material that the robotic system is constructed from have an effect on this. If softer material is selected as part of the robotic chassis, it may prevent damage to the surrounding environment especially if the robotic system fails it can be pulled by its tether without snagging on sharp edges.

5.5. To withstand the hazardous environment

The type of robot, its application and its relationship to other machines and related equipment influence the design and the selection of the protective measures. The robot system and protective measures of the robot cell shall be designed taking into account environmental conditions like surrounding temperature, humidity, electro-magnetic disturbances, lighting, etc. These can lead to some requirements for the surrounding environment due to technical restrictions. The robot and robot system and cell components shall be chosen to withstand the expected operational and environmental conditions (International Standards Organization (ISO), Robots and robotic devices — Safety requirements for industrial robots Part 2: Robot systems and integrations.10218-2:2011, 2011).

"Equipment and wiring which is incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in its most easily ignited concentration." This is achieved by limiting the amount of power available to the electrical equipment in the hazardous area to a level below that which will ignite the gases eliminate potential causes of ignition. Sensors to be part of the robotic system such as a temperature and gas sensor.

These particular sensors are compulsory to be onboard the robotic system to continuously measure that levels of heat generated by the electrical components to ensure they do not reach a limit of 38℃ which can lead to ignition. Similar to when an engineer is inspecting the fuel tank and requires sensors to monitor the atmosphere to prevent an increase in the levels of toxic vapor the same procedure applied to the that of the robotic system to monitor the conditions within the fuel tank, specifically the vapor concentration and temperature of the environment.

By knowing the temperature limit of the jet fuel for an explosion to occur, temperature sensors can be set to this limit and will be continuously measured throughout the inspection period to ensure temperature remains at a steady condition of the fuel cell and the heat generated from the electronic parts. Monitoring the conditions of the fuel tank can prevent explosions. For example, referencing the table of JP 8 fuel conditions to obtain the appropriate LEL point. The safe entry condition for a human personal is at 600 parts per million whereas the use of non-intrinsic safe equipment is 300 PPM. The best ways to control explosion is to keep the fuel vapor concentration below the LEL and Lower Flammability Level (LFL) preventing it from reaching its flammable range. Portable gas detectors can be used to monitor oxygen and flammable vapor. Oxygen concentration should be between 19.5 and 23.5 PPM. Fire risks increases if it goes above 23.5.

Another design method to prevent any hazardous substance coming into contact with electronic components is by securely enclosing the electronic system. This is achieved by selecting miniature electronic elements of the robot and encasing them with explosion proof material that will not be affected by the toxic environment. Since batteries, motors and control systems are not intrinsically safe, they need to be put together in a compact structure and encased in explosive proof material.

A number of robotic system developers have tackled the problem of the ignition factor by completely avoiding having electronic parts in the environment. This is achieved by keeping the electronic system body outside of the area of inspection and instead use a continuum arm attached to the support body to go inside the area of inspection. The continuum arm does not contain any components that can lead to ignition or explosion. Many robotic systems select suitable material such as high strength steel that is acceptable for hazardous atmosphere.

The second approach is to ensure that only intrinsically safe electronic components are used in the robot build but this does not necessarily mean that all components can be intrinsically safe. The effect of the robotic system being continuously used in a toxic environment should be taken into account. The impact of corrosion cannot be fully eliminated during the entire life cycle of the robots' operations. The robotic system will have to be maintained and thoroughly cleaned and inspected after each use.

It is necessary to identify the hazards and to assess the risks associated with the robot and its application before selecting and designing appropriate safeguarding measures to adequately reduce the risks (International Standards Organization (ISO), Robots and robotic devices — Safety requirements for industrial robots Part 2: Robot systems and integrations.10218-2:2011, 2011). The technical measures for the reduction of risk are based upon the following fundamental principles: the elimination of hazards by design; or their reduction by substitution and preventing operators coming into contact with hazards; or controlling the hazards by achieving a safe state before the operator can come into contact with it.

5.6. Retrieval method in case of failure within the fuel tank

In the case of a failure of the robotic system whilst it is within the fuel tank, an effective method of retrieval will be required. Leaving the robotic system within the fuel tank will create detrimental complications to the aircraft as it will not be operational. A tether is the most suitable option for this requirement and will be attached to the robotic system. If the robotic system was to fail within the fuel tank it can be pulled out manually. Manually drawing the robotic system out of the fuel tank has its own implications such as snagging against sharp edges, friction and chaffing, obstruction between structures with components in the fuel tank. There are disadvantages over applying a tether to the robotic system. However the advantages of applying a tether in this particular use case outweigh the complications of using a tether and also introduces many multifunctional benefits. For this particular robotic system, the benefits of a tether are:

1. Manually accessible retrieval system in case of failure.
2. Reduction in payload of the robot since a large battery pack will not be required onboard of the robotic system. The need of recharging the robotic system throughout inspection procedures will be eliminated since a continuous power supply is provided.
3. Due to the hazardous nature of the environment that the robotic system is placed within there are many restrictions when it comes to selecting a suitable power source. A wide range of power sources are not acceptable in the ignition prone environment (Trevelyan, Kang, & Hamel, 2008). Therefore, it is important to take into consideration the operating temperatures of each electronical component which tend to range between $45℃ - 85℃$. The key requirement for the power supply is to ensure that enough power is provided to the robotic system for the onboard sensors and manipulators to move effectively.

   The tether power supply allows continuous power source to the robot which is of a great advantage. Many precautions have to be taken into consideration such as the length of time of the inspection procedure. An approximation of the time spent on an inspection task can range between 30 minutes to an hour depending on the complexity of the task. This would require continuous monitoring of the temperature of the electrical components on board the robot to ensure that they do not overheat as this would increase the risk of explosion. This can be monitored with the use of multiple temperature sensors. The robotic system for this particular use case has to be relatively small in size however, requires a reasonable amount of power source due to the various sensors and manipulator mechanism that would be onboard the system. The typical operating voltage of components such as DC motor, LED lighting modules and servo motors is between the limits of 5V-12V. Batteries can be added to the system to supply a power source however, because this proposed robotic system requires a tether a CAT5 ethernet cable is one way to provide both a power and communication supply with up to 24W-25.5W power intake through the tether.
4. The tether also works as a communication system between the controller and robotic system. It is used to transmit data such as images, videos and sensor feedback in real time continuously at high bandwidth. This is extremely reliable in comparison to wireless transmission. While wireless transmission eases mobility, the nature of the wing tank environment affects its effectiveness. Because of the cluttered environment there are metal components such as piping and electrical wiring which can cause disruption between the wireless LAN devices and infrared transmitters (Niemeyer, Preusche, & Hirzinger, 2008). The tether connection provides a reliable link between the control unit and

robot. Sensor measurement data can be transmitted back and forth uninterruptedly. As stated above in the power section a CAT5 Ethernet cable can be applied to the system, where communication can reach between 80m-100m covering long ranges. A power over ethernet (PoE) allows a combination of supplying both communication and power to the robot and requires not set operating time limit.

5. For the complex fuel tank geometry and uncertain internal condition, the robotic system needs to be manually controlled or semi-autonomous, where the microcontroller is connected by a tether between the robot and computer (wired control) allowing direct control. With this method of control, complex behaviors can be programmed. Additionally, there should be multiple sensors onboard the robotic system. The sensors are to provide necessary feedback so that the operator can adjust the motion or force of the mechanical movements of the robotic system in a closed loop control system.

   Sensors such as motor encoders measure the distance and speed the robotic system has travelled. This is essential to ensure that the speed of the robotic system is measured throughout its navigating path across the fuel tank and can be continuously adjusted by the operator. This ensures accurate positioning and avoid collision within the cluttered environment. This similarly applies to manipulation technology, such as a robotic arm with an end effector. This requires high levels of movement precision to ensure desired robot behaviour. Ultrasonic Sensors (UT) are required on board the robotic system to provide feedback on the distance between the robot and any obstacle. Accuracy of the control system is important as it defines the limits of errors of an instrument at normal operating conditions. To improve the accuracy, feedback elements can be used. Overall a closed loop control from sensor measurements allow to maintain the robot performance, with the benefit of flexible programme control and ability for complex tasks.

The dimensional specifications of the tether are that it should be approximately 3m-4m in length enough for the robotic system to move throughout the surface area of the fuel tank. The tether dimensions should remain as minimum as possible between 5mm-8mm in width to prevent obstruction within the fuel tank. The tethered solution provides enhanced independence and ensured bandwidth.

6. PROPOSED ROBOTIC SYSTEM DESIGN

This section introduces the basic design concept of a robotic system based on these set of requirements. This can be the starting point to further develop into a more detailed concept.

This concept design focus primarily on the mobility through a fuel tank, along with a suitable method for visual inspection in hard-to-reach spaces. Awkward inspection positions can be reached by combining a linear actuated telescopic mechanism onboard a mobile robot platform which has the capability to reach confined spaces. This combination has the potential to meet the requirements of fighter wing tank inspection.

The concept of operation is to carefully drop the robotic system vertically through the entry access panel on the top of the wing and manoeuvred to a midpoint between the AFT and FWD fuel tank. Once the robotic system reaches this point it will use the actuation probe on board to extend in constrained spaces of the fuel tank, as illustrated in Figure 4 (Eurofighter Typhoon Cutaway Drawing, n.d.). This concept adapts the current manual RVI methods and merge this onto a mobile platform, introducing autonomy to assist with the current process of fuel tank inspection. This overall proposal has benefits such as reducing the exposure to toxic chemicals and the time spent in accessing confined spaces. In order to validate the robotic system design and ensure that it can successfully fulfilled the requirements, several tests will be completed. These are briefly touched upon in the following section. A test rig setup mimicking the fuel tank environment would be developed to conduct the tests in.

Figure 4. Typhoon wing structure illustrating robot direction of movement (Eurofighter Typhoon Cutaway Drawing, n.d.).

7. PROPOSED TESTS FOR ROBOTIC SYSTEM VALIDATION

Unforeseen circumstances such as break down of the robotic system throughout an inspection process can lead to many complications to both the robot and the environment. Therefore, to minimise the occurrence of such cases it is important to incorporate and develop effective methodologies that are capable of verifying and validating robotic systems with the application of computer vision, machine learning algorithms, as well as health monitoring.

Prognostics and Health Management (PHM) has gained considerable attention within the robot system domain as it can help inspection decision makers increase the safety and reliability of robots while reducing their maintenance costs by providing accurate predictions concerning the remaining useful life (RUL) of critical components/systems as highlighted by the work by (Fisher, Collins, Dennis, Luckluck, & Matt, 2018).

There are also rules and regulations to comply by to certify that the development of a new robotic system is safe enough to be used within a practical environment. Standards have been developed to ensure that the robotic system aligns with these for example ISO standards and safety regulations provide guidance on proving compliance of a system which has been illustrated throughout Section 5 in this paper.

The aim of verification is to ensure that the system matches its requirements. Requirements are classified in two groups knows as informal and formal. Informal requirements tend to be hard to assess if or how the system corresponds to them (Fisher, Collins, Dennis, Luckluck, & Matt, 2018). Formal verification includes precise requirements in mathematical form and comprehensive mathematical analysis of the system. Model checking is a common verification method in which specification is checked against all possible executions of the system. An example of this is simulation-based testing, with the use of Monte Carlo techniques in order to cover a wide range of practical situations by testing different types of scenarios.

Validation is the process of confirming that the final system adheres to its intended behaviour once it is active in its environment and to ensure that it meets the end user's needs. The are many approaches to carrying out validation, incorporating diverse aspects, but typically involving the assessment of accuracy, repeatability, usability, resilience, etc. (Fisher, Collins, Dennis, Luckluck, & Matt, 2018).

In given context Verification and Validation requires a range of techniques, from formal safety verification, through testing, to in-situ evaluation and monitoring. However, it is impossible to accurately model realistic characteristics of the environment, due to uncertain and continuous dynamics and exploration of all possibilities via techniques such as model-checking is infeasible. (Dinmohammadi, et al., 2018).

Recent work has been introduced focusing on developing an architecture for verification and validation process particularly for robotic system design. Several models are integrated together each focusing on a specific set of requirements. Within the architecture there are four models:

1. An interaction model used to capture modes and preferences in user interaction. It primarily focuses on what information is provided by the operator to explain the robot's actions. In this particular case the robot will be controlled by the operator therefore, focusing on how effectively will the robotic system be able to adhere to the operators commands and conduct given instructions.
2. A self-model, wherein the robot has a dynamic description of the (expected) behaviour of its own system components; robot arms, sensors, control systems, actuators, process tooling, power supplies, or planning systems. For each one of these subsystems there would be a formal description of the expected behaviour that the agent can use to monitor the various subsystems.
3. A task model, capturing the set of tasks the robot must undertake for example inspection.
4. A safety model, capturing the safety considerations identified in initial certification. The safety model in particular is required to cover how the system is operating, what are the safety requirements of the operational environment it is encountering and what responses is the system conducting. For this particular case the hazardous nature of the fuel tank has to be taken into great consideration and set requirements of how the robotic system should manoeuvre within this space, taking into consideration collision avoidance aspects.

Formal verification of the robotic system is to be completed with the application of extensive simulation testing as the system must inhabit the real-world, hence extensively test its behaviour, in all the above aspects, in more realistic environments. Once this is completed experimental test rigs can be developed to test the robot in an actual physical environment.

For the purpose of fighter wing tank inspection, the following tests include:

1. To fit within the dimensions of the environment. This would be tested by placing the robot in a 70mm size hole and analyse whether the robot can move freely within this space. The robotic system is tested on the maneuvering and turning through several holes at different angles provided in Table 1.
2. Conduct inspection in confined space. The mobile platform of robotic system should reach a specific boundary and use for example, the onboard manipulator arm to scope a hard to reach are of inspection (by the movement of extending and contracting). Test the flexibility in robot chassis and manipulator mechanism

in confined space. Minimum movement required within a compact space.

3. Conduct visual inspection in dark conditions similar to the fuel tank environment. Therefore, place the robot in an area of the test rig where there is low visibility . Onboard lighting source to be tested by capturing images and analyzing them to define whether visual characteristics of defects are clear. A corroded bolt will be analysed in order to see whether the method of inspection is effective in capturing visual signs of corrosion such as discolouration.

4. Effectively navigate around obstacles. The robot will be given a task to maneuver around a number of different shaped obstacles that may represent fuel piping for example. This will test how effectively the robot and operator are able to interact with each other and move around these structures.

5. To withstand the hazardous environment of the fuel tank. Develop a test rig mimicking the atmospheric conditions of a fuel tank. For example, testing the mobility method to see how effective it is to pass through fuel residue. Monitor onboard gas sensors and evaluate whether they are able to detect changes in oxygen levels. This specific validation test requires extensive analysis with precautions.

8. ADVANTAGES AND CHALLENGES

Using robotics to inspect fighter fuel tank has multiple advantages. First of all, the safety of the personnel can benefit significantly as it eliminates the exposure of toxic hazardous substances. The second advantage would be eliminating/reducing the requirement to dismantle subassemblies since the mobile robotic system can maneuver around obstacles and enable greater coverage of an area that may be difficult to access. This could reduce both the preparation time of the fuel tank and downtime during maintenance to achieve quicker turnaround. Other benefits include parameter limitations such as the LEL value, which may be adjusted, and the full ventilation of the fuel tank may not be necessary since personnel do not need to enter the fuel tank.

There are however still challenges for designing a robotic system for fuel tank inspection. One of the most crucial being the physical design of the robotic system. The robot has to be able to manoeuvre within the fuel tank without colliding into the various obstacles within the structure of the fuel tank to not create damaging impacts. This is predominantly applied to rigid body robotics systems. Whereas if a robot with soft material is to be developed this may have less of an impact on its surrounding structure. This particular challenge integrates with the question of what if the robotic system failed inside the fuel tank? This leads to the question, what would be the best option to retrieve the robotic system? The most reasonable decision would be to apply a tether to ensure that if it fails it can be manually pulled back. However, this is challenging since the internal structure of the fuel tank is very complex and if the robotic system snagged onto the edge of a fuel transfer hole it can lead to serious damages. Hence, the selection of material for the robotic system construction is extremely important. An effective method of retrieval should be evaluated.

9. CONCLUSION AND FURTHER WORK

When studying the variety of robotic systems applications across different industries, there are still many challenges to overcome when developing, verifying and validation a robotic system for complex environments. This paper provides a summary of the design principles and requirements for a novel robotic system for fuel tank inspection, taking into consideration the challenging characteristics of the fuel tank environment. This project is multifaceted and multiple areas of focus have to be completed effectively in order to create a suitable system. The requirement process provides a systematic approach to keep all the design areas in sync effectively. This research contributes the detailed requirement elicitation in which current robotics research are sparse in this particular area. A breakdown of the requirements set for such a complex system has been evaluated. The development of such a robotic system can revolutionize many maintenance practices. The current work to date has propose a novel inspection technique for aircraft fuel tank inspection. Future work will focus on detailed evaluation of the robotic system design in coherent with the V&V model, incorporating necessary testing and from the basis of this, the development of a mechanical prototype is to be derived.

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